A Proposition 65 Risk Evaluation of Lead, Nickel, and Chromium for Redacted Guitar Strings

Edmund A. C. Crouch, Ph.D. and Laura C. Green, Ph.D., D.A.B.T.

Prepared for

Redacted

December 23, 2023

Green Toxicology LLC

Crouch@GreenToxiciology.com
Green@GreenToxicology.com

Table of Contents

1. Overview and Introduction

This assessment addresses whether typical use of Redacted guitar strings would require a warning under the State of California's Proposition 65.[1] In particular, we focus on whether the presence of lead, nickel, and/or chromium would result in a dose to an average guitar player that would pose any "notifiable" risk for either cancer or reproductive toxicity.

As explained below, these metals in these strings, including in their ball-ends, would pose no such risk, and thus require no such warning.

Of course, *a priori*, it might seem odd to imagine that guitar strings *could* be unhealthful to people who use them. No one eats these strings; no one cooks with these strings; these strings do not evaporate or otherwise pose an inhalation risk; and no one applies these strings to their skin

[1] Safe Drinking Water and Toxic Enforcement Act of 1986 (California Health & Safety Code §25249.5–25249.14).

Crouch@GreenToxiciology.com
Green@GreenToxicology.com

as a cosmetic. Nonetheless, people's fingers do touch these strings; and the results of "wipe testing," presented below, indicate that infinitesimal quantities of all three metals are, or at least might be, available on the surface of these strings.

These metals are present in guitar strings because of the use of nickel plating, bronze, brass,[2] carbon steel, and stainless steel to construct those strings. Because these metals contain trace levels of lead, the residual presence of lead in these strings from these materials is practically inevitable, and its concentration is controlled at sufficiently low levels by the specifications of raw materials (wire) containing tin, bronze, or brass. The ball ends of the strings are constructed of leaded brass, so they are considered separately below. Nickel is deliberately used in the nickel-plated strings, and chromium is a constituent of the stainless steel used for some strings (with nickel specified to a low level), and carbon steel contains trace levels of lead, nickel, and chromium.

2. Proposition 65 "No Significant Risk Levels" and "Maximum Allowable Dose Levels"

The Reproductive and Cancer Hazard Assessment Branch of OEHHA is the lead office for the implementation of the Safe Drinking Water and Toxic Enforcement Act of 1986 (Proposition 65), and in that role has established no significant risk levels (NSRLs) for some carcinogens and maximum allowable dose levels (MADLs) for some chemicals causing reproductive (including developmental, female reproductive, and male reproductive) toxicity. The latest available list of these levels, and additional information, is available from OEHHA at https://oehha.ca.gov/proposition-65/proposition-65-list.

2.1. Lead

Lead and lead compounds are listed for risk of cancer, with an NSRL of 15 µg/day for lead, and higher values for several specific lead compounds (based[3] on the lead content of those compounds). Lead[4] is listed also for risk of developmental and male and female reproductive toxicity, with a MADL of 0.5 µg/day.

2.2. Nickel

Nickel and nickel compounds generally, and specific nickel compounds, are listed as carcinogens, with NSRLs listed only for nickel refinery dust and nickel subsulfide. Nickel and nickel compounds are carcinogenic only by inhalation and none of the exposures to guitar strings are by inhalation. Soluble nickel compounds are listed as developmental and male reproductive toxicants, but no MADL has been promulgated. As detailed below, the majority of any nickel exposure from guitar strings would be to the oxide or hydroxide, which are both insoluble in

[2] The bronze and brass are not "leaded" — no lead is deliberately added; see Section 3.1.
[3] See https://oehha.ca.gov/media/downloads/crnr/leadcompoundsoralnsrlsfinal.pdf.
[4] Although this listing is stated as "lead" alone on the Proposition 65 lists, the basis for the listing is the OSHA regulations in which (1910.1025(b)) "Lead means metallic lead, all inorganic lead compounds, and organic lead soaps. Excluded from this definition are all other organic lead compounds." In practice, the OSHA regulations specifying levels of lead exposure apply to the lead component of included compounds. Here, for Proposition 65 purposes, we interpret the MADL as applying to lead and the lead component of any compound.

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

water according to OEHHA's definition (<0.1 mole per liter at 20°C, OEHHA, 2019), so would not require any notice. However, some fraction of the exposure may be to soluble nickel, since experiments with artificial sweat indicate some dissolution of nickel compounds from nickel plating.

Nickel is essential in plants and microorganisms, and trace intakes may be beneficial for animals including humans (Nielsen 2012, 2021, Institute of Medicine 2001, 2006). Median adult nickel intake from foods was reported to be 74 to 100 µg/day in 1984, with another approximately 5 µg/day from supplements. No Adequate Intake could be derived, but a Tolerable Upper Intake Level of 1 mg/day for adults was determined (Institute of Medicine, 2001and 2006).

When no MADL has been set for a chemical on the Proposition 65 list for reproductive toxicity, as is the case for soluble nickel compounds, no warning is required if the responsible party can show

> *...that the exposure will have no observable effect assuming exposure at one thousand (1000) times the level in question for substances known to the state to cause reproductive toxicity, based on evidence and standards of comparable scientific validity to the evidence and standards which form the scientific basis for the listing...* (California Health & Safety Code, §25249.10(c))

and, pursuant to the Act's implementing regulations

> *When data do not allow the determination of a NOEL [No observed effect level], the lowest observed effect level shall be divided by 10 to establish a NOEL for purposes of assessment.* (California Code of Regulations, § 25803(a)(8)).

Importantly, the regulations also require (§ 25803(a)(4) and (5)) that animal bioassays meet generally accepted scientific principles, and the NOEL should be based on the most sensitive studies deemed to be of acceptable quality.

In this case, the NOEL from the most sensitive study that meets the quality requirements of the Act is 1.12 mg/kg-day, as derived in OEHHA's development of an oral reference level for nickel (OEHHA, 2012), based on two studies in rats (NiPERA, 2000a,b). However, in this derivation OEHHA failed to take account of the within-litter correlations, and the LOAEL determined by OEHHA in the first (ranging) study was not corroborated in the second detailed study. Taking account of the within-litter correlations (e.g. by treating the dam or litter as the unit of experimentation), the NOEL should be about four times higher (EFSA, 2015).

2.3. Chromium

Hexavalent chromium (Cr VI) compounds are listed as carcinogens and male developmental toxicants, with an NSRL of 0.001 µg/day by inhalation and a MADL of 8.2 µg/day by the oral route. Trivalent chromium (Cr III) compounds and zero valent (metallic) chromium are not on the Proposition 65 list, so do not require notice under the Act. Chromium potentiates the action of insulin *in vivo* and *in vitro*, but its essentiality is uncertain. An Adequate Intake of 35 µg/day for males 14 through 50 years of age, 24 µg/day for 14 through 18-year-old females, and 25 µg/day for 19 through 50 year-old females was determined based on typical diets, and no Tolerable Upper Intake Level was set because of insufficient data (Institute of Medicine, 2001

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

and 2006). Cr VI oral intake at these levels would be reduced to Cr III prior to absorption by the reductive capacity of the upper gastrointestinal tract (Institute of Medicine, 2001). Exposures to chromium from guitar strings is to metallic or trivalent chromium only, so no notice is required under the Act. However, in what follows we evaluate total exposure to chromium.

2.4. Exposure assumptions

In assessing exposures to carcinogens, the relevant time frame for exposure is the long-term average, where long term is typically taken to be a 70-year lifetime, unless more specific and scientifically appropriate data are available.[5]

In assessing exposures to reproductive toxins, "[w]*here a maternal exposure to a chemical listed as causing reproductive toxicity has an effect on the conceptus (embryo or fetus), the level of exposure shall be based on the reasonably anticipated rate of exposure for the mother during the nine-month gestation period.*"[6] And in the absence of more specific and scientifically appropriate data, "*[w]hen the applicable reproductive effect is upon the adult female or conceptus, human body weight of 58 kilograms shall be assumed*."[7]

3. Concentration of lead, nickel, and chromium in or on Redacted guitar strings

3.1. Redacted string raw materials and measurements

Redacted guitar strings are available for acoustic and electric guitars ("acoustic/electric") and bass guitars, sold as sets or individual strings. The highest pitched acoustic/electric strings (one to eight per set for acoustic guitars, three to eight per set for electric guitars) are "anti-rust plain steel" (called just plain steel strings), a single steel wire (ASTM A228) that is nickel-plated to AMS2403M specification as an anti-rust treatment, with no further covering. The strings for lower pitches (with higher gauges, including all bass guitar strings) have steel cores wrapped with wire made from 80/20 bronze[8] (ASTM B134 C24000), phosphor bronze (ASTM B159/B 159M C52100), steel (AISI 1006) plated with nickel, or stainless steel (AISI 430). All the wrapped strings are coated with proprietary fluoropolymer coatings — Redacted. The nominal overall length of the acoustic/electric strings is 42.5 inches, with wrapping over 33.5 inches, while the bass guitar strings are nominally 50.5 inches long with wrapping over 39.25 inches. The plain strings are nominally 41.125 inches long. All the strings have a "ball end" (used to anchor the fixed end of the string) consisting of a cylindrical brass tube (small, 0.157 OD x 0.087 ID x 0.117 inches for acoustic/electric strings; large, 0.235 OD x 0.125 ID x 0.190 inches for bass strings) to which the string is securely fastened.

ASTM B134 C24000 brass and ASTM B159/B 159M C52100 phosphor bronze both specify a lead content <0.05% (<500 ppm), but do not have explicit limits on either nickel or chromium, which may be trace impurities. AISI 1006 steel specifications do not contain explicit limits on lead, nickel, or chromium, but none of these are specific alloying components, so can be expected at only trace levels. AISI 430 stainless steel has a nominal composition of 16–18%

[5] See Title 27, Division 4, Chapter 1, § 25721, California Code of Regulations.
[6] See Title 27, Division 4, Chapter 1, § 25821, California Code of Regulations.
[7] See Title 27, Division 4, Chapter 1, § 25803(b), California Code of Regulations.
[8] This is the name given to the Redacted product. Technically this is brass, not bronze.

Crouch@GreenToxiciology.com
Green@GreenToxicology.com

chromium and <0.75% nickel, with no specification on lead, although again lead can only be expected to be present at trace levels. There is no explicit limit on either lead or chromium in the nickel plating, but both of these elements may be trace contaminants. The brass of the ball ends is specified to contain 1.6 – 3.5% lead, 0.3% nickel, and nominally no chromium.

Table 1 summarizes some specifications of string sets in the Redacted line.

Table 1 Summary of Redacted string set specifications

Product line	**Strings per set wrapped /plain**	**Ball end**	**Wrapping wire specification**
80/20 Bronze Acoustic Guitar Strings	4/2, 3/3, 4/4, 5/7	Small	ASTM B134 C24000 80/20 Brass
Phosphor Bronze Acoustic Guitar Strings	4/2, 3/3, 5/7	Small	ASTM B159/B159M C52100 Phosphor Bronze
Nickel-plated Steel Electric Guitar Strings	4/2, 3/3, 4/3, 5/3, 4/8	Small	Nickel-plated AISI 1006 steel
Nickel-plated Steel Electric Bass Strings	4/0, 5/0	Large	Nickel-plated AISI 1006 steel
Stainless Steel Electric Bass Strings	4/0, 5/0	Large	AISI 430 Stainless Steel
80/20 Bronze Acoustic Bass Strings	4/0	Large	ASTM B134 C24000 80/20 Brass
Nominal specifications: omitting specified maximum trace elements other than lead, nickel, or chromium ASTM B134 C24000 80/20 Brass; nominally 80% copper, 20% zinc, <0.05% lead ASTM B152/B159M C52100 Phosphor Bronze: nominally 92% copper (incl. silver), 8% tin, <0.05% lead AISI 1006 steel: nominally 99.5% iron, 0.4% manganese, 0.1% carbon AISI 430 Stainless Steel: nominally 83% iron, 17% chromium, <0.75% nickel All wrapped strings have a fluoropolymer coating (Redacted) Plain strings are plated with a nickel-containing anti-rust coating.			

3.2. Wipe test results

Wipe testing was performed on representative strings of the Redacted line of acoustic, electric, and bass guitar strings. The strings chosen for the tests were the highest gauge (largest diameter) strings in string sets for each type of string.

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

The wipe tests were conducted by Element Materials Technology (https://www.element.com/) according to their procedure SFS-0116, Rev 14, an adaptation of method NIOSH 9100 (see Appendix B: Element Materials Technology Laboratory Report on Job). The adaptation of NIOSH 9100 (which calls for wiping of a 10 × 10 cm flat area "or other standard size") is described by:

> *The entire length of the string was wiped with firm pressure 4 times (in one direction), including the ball at the end of the string. The exposed side of the wipe was folded in and the area was wiped in the opposite direction with 4 strokes. The wipe was folded once more and the area was wiped in the original direction with 4 strokes." (Element Materials Technology).*

The wipes used were Ghost Wipes (Environmental Express, https://www.environmentalexpress.com/ee/s/product/detail/01t4W00000FjULpQAN), which are pre-wetted wipes of nonwoven polyvinyl alcohol fiber compliant with ASTM E1792 for lead in dust.

Each Ghost Wipe was used to wipe a single string using this protocol, and the whole procedure was repeated in triplicate to obtain three Ghost Wipes per string type. Then:

> *The entire wipe (~3-5 g) was digested in a capped vessel with 1 ml of nitric acid and 3 ml of hydrochloric acid for 1 hour on a block digester set at 90°C. The digestate was cooled, internal standards were added, and then the digestate was diluted to a final mass of 100 g with high-purity water. The sample mostly dissolved." (Element Materials Technology).*

The solution was analyzed by inductively coupled plasma-mass spectrometry (ICP-MS) to obtain the total mass of lead, nickel, and chromium on the wipe (hence corresponding to the total amount of material removed from a single string). Blank Ghost Wipes were also analyzed in the same manner to determine background levels in the wipes.

The results of testing, including the blank wipes, are shown in Table 2, as measured µg/Ghost Wipe (*i.e.* µg of surficially available metal per string). For our assessment, for nickel and for chromium, we use the average values and subtract the average blank wipe values; while no subtraction was needed for lead, since no lead was detected in any of the blank wipes.

Strings that are thickly coated with polymer would presumably prevent dermal contact with the metal of the strings. However, Redacted strings have thin coatings to optimize the tone of the string; and such coatings may be sufficiently thin as to be microporous, either allowing some contact with the metal or allowing metal (or metal oxide or metal salt) migration to the surface of the coating. If so, then the surface of the coating would correspond reasonably well to a metal surface (at least from the point of view of the thin metal/oxide/salt coating on it). If not, then once any metal coating on top of the polymer was cleaned off, the polymer would remain clean and no further metal would be accessible until the coating wore out, at which point the strings would be replaced or again the metal surface would correspond to bare metal. In what follows,

Green Toxicology LLC

Crouch@GreenToxiciology.com
Green@GreenToxicology.com

we evaluate the coated strings as if they were bare metal, so that we may obtain a conservative (that is, high) estimate of potential exposures to guitar players.

The results of the wipe tests indicate that the material wiped from the strings does not match the specifications of the base metal of the strings in many, if not all, cases. For example, the brass wrapped strings show lead wipe fractions substantially above the specified 0.05% maximum for the brass wrapping wire. For this reason, in what follows we assume that the wipe tests are reflective of the composition of the material that would be rubbed from the strings to a players' fingers, except for the ball-ends which are treated separately in Section 5.5.

Table 2 Results of the wipe tests on representative strings (the largest gauge of each type of string)

			Ghost Wipe data (µg/string)		
Sample Description	**Gauge (inches)**	**Sample ID†**	**Chromium**	**Lead**	**Nickel**
Redacted 80/20 Brass Acoustic Guitar String	0.07	Redacted -1	0.23	0.1	0.34
		Redacted -2	0.49	0.079	0.42
		Redacted -3	0.05	0.066	0.19
		Average	0.257	0.082	0.317
Redacted 80/20 Brass Acoustic Guitar String	0.059	Redacted -1	0.2	0.13	1.3
		Redacted -2	0.17	0.084	0.98
		Redacted -3	0.19	0.088	1.1
		Average	0.187	0.101	1.127
Redacted Phosphor Bronze Acoustic Guitar String	0.056	Redacted -1	0.095	0.21	0.84
		Redacted -2	0.077	0.12	0.38
		Redacted -3	0.12	0.25	0.89
		Average	0.097	0.193	0.703
Redacted Nickel-plated Steel Electric Guitar String	0.08	Redacted -1	0.073	0.061	7.8
		Redacted -2	0.069	0.088	7
		Redacted -3	0.052	0.091	4.7
		Average	0.065	0.080	6.500
Redacted Nickel-plated Steel Electric Guitar String	0.08	Redacted -1	0.068	0.064	16
		Redacted -2	0.06	0.063	5.6
		Redacted -3	0.066	0.049	14
		Average	0.065	0.059	11.867
	0.049	Redacted -1	0.21	0.08	2.4
		Redacted -2	0.17	0.061	3.4

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

			Ghost Wipe data (µg/string)		
Sample Description	**Gauge (inches)**	**Sample ID†**	**Chromium**	**Lead**	**Nickel**
Redacted Nickel-plated Steel Electric Guitar String		Redacted -3	0.17	0.064	1.9
		Average	0.183	0.068	2.567
Redacted Nickel-plated Steel Electric Bass String	0.135	Redacted -1	0.37	0.15	5.1
		Redacted -2	0.29	0.18	4.4
		Redacted -3	0.23	0.22	8
		Average	0.297	0.183	5.833
Redacted Stainless Steel Electric Bass String	0.13	Redacted -1	5.3	0.54	2.3
		Redacted -2	4	0.66	1.7
		Redacted -3	4.2	0.12	1.5
		Average	4.500	0.440	1.833
Plain Steel‡ Acoustic/Electric Guitar String	0.022	Redacted -1	0.072	0.093	6.4
		Redacted -2	0.065	0.19	6.4
		Redacted -3	0.066	0.2	7.6
		Average	0.068	0.161	6.800
Blank Ghost Wipe	N/A	Redacted -1	0.036	< 0.005	0.016
		Redacted -2	0.04	< 0.005	0.021
		Redacted -3	0.032	< 0.005	0.019
		Redacted -1	0.035	< 0.005	0.02
		Redacted -2	0.037	< 0.005	0.16
		Blank-1	0.033	< 0.005	0.027
		Blank-3	0.054	< 0.005	0.028
		Blank-5	0.043	< 0.005	0.017
		Average	0.03875	<0.005	0.0385

† Sample IDs are as given in Appendix B: Element Materials Technology Laboratory Report on Job .
‡ Plain steel strings are nickel-plated and uncoated. All other strings are wrapped and coated.

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

4. Initial screening evaluation

4.1. Lead

The wipe data presented in Section 3.2 confirm the trace nature of any lead present in the construction materials of the strings, and indicate that the worst-case potential exposure to lead from a single string might occur with the Redacted stainless steel wrapped bass strings. The quantity of lead detected from the tested stainless steel wrapped bass string amounts to an average of about 0.44 µg per string with 12 wipes per string. With conservative assumptions, to obtain an ingestion exposure of 0.5 µg/day (the MADL for lead) would require that a user *lick* over the whole length of such a string (including the ball end) about twice or more per day, or somehow obtain an equivalent exposure (assumes that two licks – to cover both sides of the string – would be sufficient to remove all the surface lead removed by 12 wipes and that the surface lead refreshes between licks; or equivalent assumptions). For a 5-string bass guitar strung with the Redacted stainless steel wrapped strings (the worst-case), the total surface area of the strings (all wrapped) accessible after stringing is about 3 times the surface area of the tested string,[9] ignoring the ball ends which are normally not accessible after stringing, giving a total lead mass of 1.3 µg, so that an equivalent exposure would require daily licking more than three quarters of the whole strung area daily (since such licking would only contact the top half of the string).

All the other average lead measurements give lower estimates for lead per string or per strung area, indicating that even more extreme exposure-scenarios would be required to obtain an ingestion exposure of 0.5 µg/day or more. Such behaviors are certainly not those of an average user (whether amateur or professional musician), and equivalent behaviors are difficult to imagine. In other words, because wiping the guitar strings resulted in only vanishingly small amounts of lead-transfer, it is essentially inconceivable that guitar players could be at any notifiable risk to health from this metal under Proposition 65.

Nonetheless, in what follows, we utilize published measurements of transfer of metals from coins to people's fingers; in so doing, we demonstrate that the MADL for lead would not be exceeded under even conservatively estimated inputs relevant for actual guitar string uses.

4.2. Nickel

The highest quantity of nickel detected from any coated string was from the REDACTED nickel-plated steel electric string, at 11.8 µg per string.[10] REDACTED nickel-plated steel electric string sets are available in multiple combinations (see Table 1) and have both the wrapped REDACTED coated and plain steel strings in each set. The wipe tests show the plain steel strings with 6.8 µg per string. Taking account of the strung surface areas and types of strings in each set, the set with the highest total surface nickel is the 8-string set with 37 µg per set. Using a 58 kg

[9] To be conservative, for wrapped strings we assume here and subsequently that the entire wipe result comes from the wrapped portion of the tested string, ignoring any contribution from the unwrapped portion and the ball end.

[10] All measurements here and subsequently are corrected for the blank wipes.

Crouch@GreenToxiciology.com
Green@GreenToxicology.com

body mass, the total mass available on the strings corresponds to 0.64 µg /kg, so that even if this *total* available amount were to be *ingested* daily, 1,000 times the amount is less than the lowest NOEL observed for reproductive or developmental effects (Section 2.4); and this is without taking account of (i) what fraction could be ingested, (ii) whether it could renew daily, or (iii) the chemical form of the available nickel (most of which is insoluble and therefore irrelevant for Proposition 65). In other words, here again, because wiping the guitar strings resulted in only vanishingly small amounts of nickel-transfer, it is essentially inconceivable that guitar players could be at any notifiable risk to health from this metal under Proposition 65.

4.3. Chromium

The highest quantity of chromium detected on any coated string was from the REDACTED stainless steel electric bass string, at 4.5 µg per string. Chromium on the surface of stainless steel is in the form of chromic oxide (Cr_2O_3), in the III oxidation state. The chromium detected on other strings would also be in the form of chromic oxide, in the III oxidation state. Because this form of chromium is not on the Proposition 65 list, no warning is required for chromium. Despite this, we continue evaluation of potential exposures to chromium in the detailed evaluation below.

5. Detailed evaluation of exposure pathways

Average users' most extensive exposure to Redacted strings guitar strings will result from the intended use of these strings on musical instruments; that is, amateur or professional musicians playing guitars or equivalent instruments. Such musicians are certainly exposed to at least some quantity of metals from instrument strings, as is evident from literature reports of nickel allergies resulting from some players' uses of nickel-plated strings (Smith *et al*., 2006).

During this use, musicians will contact the strings with the fingers of both hands (for a right-handed player using a pick, the contact will be relatively small on the right hand). In the process, the musician's fingers will rub material (typically metal oxides or hydroxides) from the surface of the strings, and some of that material may stick to the surface of the fingers. Subsequently, some may be absorbed transdermally, and some may be ingested if there is hand-to-mouth contact.

5.1. Amounts of metals rubbed from guitar strings on to fingers

We have not located any studies with usable measurements of transfer to fingers of any metal present in only trace quantities in an alloy (as is lead in all the string materials of interest here; nickel in the brass, phosphor bronze, and stainless steel; and chromium in all but the stainless steel). However, there are studies of the transfer of major component metals from coins to fingers, primarily in evaluation of the extent of exposure to nickel from the copper/nickel/zinc alloys used in coins; and there are studies of the transfer of nickel from pure nickel and nickel alloys, including nickel-chromium-iron alloys. These studies provide information that may be used to extrapolate the potential amount of lead, nickel, and chromium transferred from the alloys used in the construction of Redacted guitar strings.

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

5.1.1. Metal transfer from coins and prepared metal surfaces

Fournier and Govers (2003) demonstrated dermal transfer of nickel (Ni), copper (Cu), and zinc (Zn) to volunteers' fingers during manipulation of French 2-franc and European 2-euro pieces taken straight from circulation ("unwashed"), after washing by 10 minutes immersion in demineralized water in an ultrasonic bath ("washed"), and after rubbing the coins to a shiny finish ("polished"). The 2-franc pieces had been in circulation for several years, and the 2-euro pieces for between 2 and 5 months. Each volunteer handled 58 coins (counting them by transferring them from one plastic container to another), with an average handling time of 2.6 seconds per coin (range about 2 to 3 sec depending on the volunteer). Each volunteer used three fingers for such handling (thumb, index, and middle finger), and the metal content[11] of material transferred to these fingers was measured. The metal content of the material transferred to the 3 fingers, per coin, in each handling, is shown in Table 3.[12]

Table 3 Total amount of metal content transferred to 3 fingers by handling, µg/coin handled, with 90% confidence limits (Fournier and Govers, 2003)

	French 2-franc coins			European 2-euro coins		
Metal	Unwashed	Washed	Polished	Unwashed	Washed	Polished
Ni	0.38 ± 0.10	0.46 ± 0.16	0.009 ± 0.004	0.23 ± 0.06	0.26 ± 0.07	0.012 ± 0.006
Cu	0.44 ± 0.10	0.24 ± 0.07	0.013 ± 0.004	1.4 ± 0.2	1.3 ± 0.2	0.10 ± 0.01
Zn	0.14 ± 0.03	0.12 ± 0.04	0.012 ± 0.003	0.26 ± 0.03	0.28 ± 0.05	0.07 ± 0.03

European 2-euro coins have a complex structure — a center disk (that has a core of nickel with a surface of nickel brass (75% Cu, 20% Zn, 5% Ni; 5.09 cm^2 surface area), and an outer ring of copper-nickel (75% Cu, 25% Ni; 7.11 cm^2 surface area including the rim, 5.33 cm^2 excluding the rim), so transfer of all three metals would be expected from the 2-euro coins; and the transfers from the unwashed and washed coins approximately match the proportions of the coin material. The results for French 2-franc coins, however, are inexplicable in terms of the base materials of the coins, since they are pure nickel (12.5 cm^2 surface area including the rim, 11.0 cm^2 excluding the rim) yet appreciable quantities (compared with nickel) of copper and zinc were transferred from such coins. The results are, however, explicable in terms of the metals removed from the surface of the coins during polishing (Table 4). Evidently, the surface of coins becomes contaminated by other metals (*e.g.* from other coins) during everyday circulation, and it is metal from this surface film that is transferred to fingers during handling.

The total masses of metal removed from these coins by polishing are large compared with the masses removable in the wipe tests of Redacted strings. For example, the nickel content of the

[11] The actual material transferred is probably a metal oxide or hydroxide, rather than pure metal, since all these metals form an oxide/hydroxide layer on exposure to air.

[12] Previous work had shown (Fournier *et al*., 2002) that iron and aluminum were detectable, but at lower levels, and other metals (tin, cobalt, chromium, manganese, lead, and titanium) were either non-detectable or present at much lower levels. Iron, aluminum and tin are components of some coins in circulation, so could have contaminated the surfaces of these coins.

Crouch@GreenToxiciology.com
Green@GreenToxicology.com

polishable nickel surface film on the pure nickel 2-franc coin was approximately 1 μg/cm^2, whereas the maximum wipe test removable nickel surface film on the nickel-plated Redacted strings ranged from 0.05 to 0.37 μg/cm^2. A nickel hydroxide surface film (the most likely chemical form of surface film on pure nickel) with 1 μg/cm^2 nickel content would be approximately 3.8 nm thick. Similarly, the nickel content polishable from the surface film on the 2-euro coin was approximately 0.5 μg/cm^2 whereas the wipe test removable nickel on the brass wrapped strings ranged from 0.006 to 0.027 μg/cm^2.

Table 4 Average metal content (μg) in surface film removed from each coin during polishing.

Metal	2-franc coin	2-euro coin
Ni	12	5
Cu	13	38
Zn	2	8

Using the data in Table 3 and correcting to a surface consisting (hypothetically) of 100% of the selected metal using the measured fractional surface metal composition of Table 4, and using the 2.6 second handling time (for reasons explained below), gives the results of Table 5 for the initial rate of transfer of metal content to the 3 fingers involved during coin handling.

Table 5 Average transfer rate per unit coin facial surface area, μg/cm^2/sec, to 3 fingers while handling coins, normalized to 100% surface availability of the given metal.

	2-franc coin			2-euro coin		
Metal	Unwashed	Washed	Polished	Unwashed	Washed	Polished
Ni	0.030	0.036	0.00071	0.087	0.098	0.0045
Cu	0.032	0.017	0.00094	0.069	0.064	0.0050
Zn	0.066	0.057	0.0057	0.061	0.066	0.016
Total	0.034	0.029	0.0012	0.070	0.068	0.0067

The results of Table 5 show relatively good consistency between the transfer rates for un-polished coins when evaluated this way,[13] and indicate that the metal transferred is probably from a surface layer of material on the coins that may differ considerably from the base material of the coin. They also show that when the surface-removable material is depleted by polishing, the transfer rates generally decrease about 10-fold or more (although only about 4-fold for zinc on the 2-euro coin). The results for the 2-franc coin after polishing show that appreciable quantities of zinc and copper remained on the surface of that coin even after polishing.

[13] Calculation of a rate per unit coin surface area may slightly underestimate transfer rates, since in the 2 to 3 seconds of picking up the coins and transferring them to another container may not result in the whole surface of the coins being rubbed.

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

The transfer rates shown in Table 5 for the unpolished coins could not, however, continue for very long without depleting the removable material. Table 6 shows the handling time in seconds required to remove the amount of material shown in Table 4 based on the measured transfer rates of Table 3.[14]

Table 6 Handling time (seconds) to remove the polishable material from coins

	2-franc coin		2-euro coin	
	Unwashed	Washed	Unwashed	Washed
Ni	82	68	57	50
Cu	77	141	71	76
Zn	37	43	80	74

Fournier and Govers (2003) also showed that there appeared to be a distinct surface layer of more readily removable material in leaching tests of little used or uncirculated coins. A short-term test of 80 minutes leaching 2-euro coins in demineralized water showed linear leaching at a rate approximately 18 times higher than long-term (1-week) tests,[15] with the total amounts per coin of Ni, Cu, and Zn removed in the 80 minutes of leaching approximating those shown in Table 4 (approximately 28 μg Cu, 8 μg Ni, and 5 μg Zn). Even the short-term leaching rates were, however, much too low to account for the transfer of metals seen in Table 3, so the primary transfer mechanism presumably involves friction rather than dissolution in sweat. The same conclusion is drawn in all the studies below that also examined leaching in water or artificial sweat.

Gwozdz and Grass (2004) evaluated transfer of metals from metal foils and metallic objects to fingers by quantifying the transfer of metal to filters that were rubbed by fingers that had previously rubbed metal foils or metal objects. The contact here may have been more intense than that recorded by Fournier and Govers (2003), since the volunteers actively rubbed the metallic objects between fingers (and then the filter). However, no attempt was made to evaluate the fraction of material on the fingers that was rubbed on to the filters. The total time taken for both operations was about 30 seconds, and we assume here that the rubbing of metal materials took 15 sec. Assuming quantitative transfer of metal from fingers to filters, Table 7 shows the total transfer rate (to finger and thumb combined) in μg/sec during the metal rubbing for those cases where the measured metal was the same as the metal of the object rubbed, and the object was primarily composed of the measured metal.[16] It can be seen that the transfer rate is very

[14] The implication is that a minute or two of rubbing a coin between the fingers will polish it fairly effectively; and this indeed works.

[15] Estimated at pH 7 by a least-squares linear fit to Figure 1 of Fournier and Govers (2003) between pH 4 and 10.1, combined with the 8 μg/coin at 80 minutes shown in Figure 3 (op. cit.). Fournier and Govers (2003) give an estimate of a factor of 7, but their corresponding stated values do not fully agree with the figures.

[16] Gwozdz and Grass (2004) also measured transfer of trace metals, but gave no information on the concentrations of those trace metals in or on the surface of the objects rubbed. Such measurements give no useful quantitative information on transfer rates, and based on the observations of Fournier and Govers (2003) discussed above they do not contradict what is shown here either qualitatively or quantitatively.

Crouch@GreenToxiciology.com
Green@GreenToxicology.com

variable in these measurements, and that for pure soft metals it can reach the transfer rates shown in Table 5.

Table 7 Transfer rate from foils or 100% metal objects during rubbing by fingers, μg/sec.

Metal	Object	Person A	Person B
Gold	Ring	0.013	0.008
	Watch	0.002	0.002
	Chain	0.001	0.036
Silver	Spoon	0.037	0.045
	Bracelet	0.025	0.043
	Necklace	0.167	0.080
Zinc	Foil	0.253	0.247
Cadmium	Foil	0.033	0.027
Tin	Plate	0.533	0.200
Cobalt	Foil	0.031	0.127
Nickel	Foil	0.160	<0.003

Subsequent measurements of metal transfer have generally focused on nickel, primarily because of the ability of nickel to induce allergic responses. Staton *et al.* (2006) developed a quantitative methodology for extraction of metals on fingers by dipping the finger in ultrapure water for 2 minutes, which gave an extraction efficiency of 91% with one wash.[17] They measured the transfer of nickel to index finger and thumb during deliberate rubbing between them of pre-cleaned British 20 p coins (16% Ni, 84% Cu) by two subjects. Staton *et al*. (2006) indicated that the quantity of nickel transferred to finger and thumb increased linearly over a period extending at least up to 15 minutes, but re-analysis[18] of their data (Figure 1) shows a more rapid initial transfer rate for the first 30 seconds (volunteer A, red line) or 10 seconds (volunteer B, blue line). The transfer rates for volunteer A were: initial 0.023 μg/sec, final 0.006 μg/sec, and for volunteer B: initial 0.018 μg/sec, final 0.0023 μg/sec, suggesting that volunteer A applied more pressure during rubbing. Prorating these transfer rates to a 100% nickel surface gives initial rates of 0.15 and 0.11 μg/sec, with subsequent rates of 0.038 and 0.015 μg/sec. While these rates are reasonably similar to those obtained from unwashed and washed versus polished coins for nickel by Fournier and Govers (2003), see Table 5, it is unclear if the implied total metal removal was

[17] An alternative method used in other studies discussed uses wipes wetted with 1% nitric acid in water (safe on skin) to achieve similar efficiency. On the other hand, Table 5 shows that pure water immersion is not effective at removing the surface layers from metals.

[18] Staton *et al.* (2006) plot the average concentrations in the 35 ml of ultrapure extraction water used for each of the finger and thumb. The fitted lines are maximum likelihood fits of a model consisting of two straight lines, optimizing the intercepts, slopes, and join time of the two lines assuming uncertainties such that the logarithm of the concentrations are normally distributed about the lines, with different standard deviations for volunteers A and B.

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

dissimilar, since Staton *et al*. (2006) did not report analysis of any other metals. The coins were "gently cleaned with high purity water and left to air dry." Such treatment, if it involved any rubbing or an immersion exceeding a few tens of minutes, could have removed some fraction of the polishable material observed by Fournier and Govers (2003), so the similarity of rates with those of Fournier and Govers (2003) may be misleading.

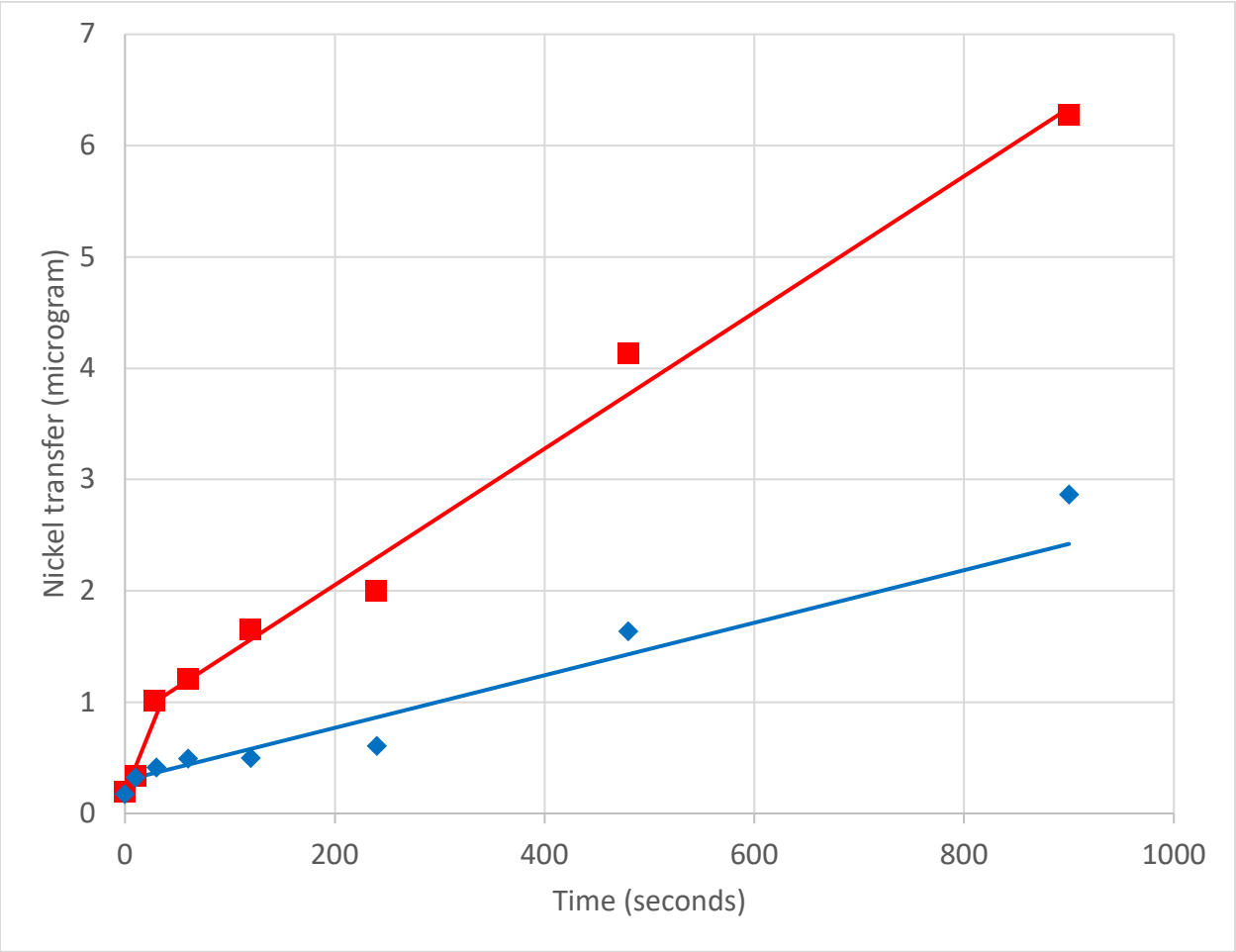

Figure 1. Nickel transfer to finger and thumb by two subjects rubbing pre-cleaned British 20p coins.

This observation of linearity with time justifies the presentation of results in Table 5, Table 7, and Table 8 as a transfer rate per unit time.

Staton *et al.* (2006) also evaluated the effect of handling pre-cleaned British 1-pound coins (5.5% Ni, 24.5% Zn, 70% Cu) for two minutes. Normalizing their results to 100% Ni, assuming that the surface Ni content of the coin corresponds to its bulk Ni content, gives the values shown in Table 8; however, while these range from about $1/10^{th}$ to equality with the values in Table 5, they may be considerably in error because of the potential difference of the surface layer from the bulk metal.

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

Table 8 Transfer rates observed by Staton *et al*. (2006), normalized to 100% Ni using bulk material concentrations

Subject	Transfer rate, µg/sec, in four experiments with 2 minutes of rubbing			
	Using 1 pound coins (Ni content 5.5%)	Using 20 p coins (Ni content 16%)		
A	0.263	0.154	0.349	0.162
B	0.330	0.113	0.159	0.124
C	0.370	0.081	0.078	0.054
D	0.239	0.071	0.096	0.052
E	0.169	0.115	0.169	0.086

Lidén *et al.* (2008a) also examined the effect of intense coin handling of 25 coins (Swedish 1-krona, 75% Cu, 25% Ni; or European 2-euro, see above) for 1 hour on nickel transfer to fingers and palm of the hand, although their measurements were of areal concentrations on small portions of the fingers and palms. They demonstrated average concentrations on the most exposed[19] parts of the fingers (thumb, index, and middle finger) ranging from 0.94 to 3 µg/cm^2, within the range expected by extrapolation from the observations of Staton *et al.* (2006) who measured an average of 22 ng/cm^2 averaged over the whole thumb and forefinger (about 100 cm^2, including the dorsal sides) after 2 minutes handling of a British 20 p coin.[20]

Erfani *et al*. (2015) evaluated finger rubbing ("touch") tests and wipe tests of 6.25 cm^2 samples of prepared pure nickel and four nickel alloys using a device that ensured a nearly constant force (3.4–3.9 N) during the rubbing or wiping. That force is within the range of fingertip forces (0.4–6.9 N) found for guitar players playing chords (Sung *et al*., 2013). Samples were prepared by grinding on wet P800 (12 µm) followed by P1200 (6 µm) emery papers, rinsing, and drying. Fingers or wipes (wetted with artificial sweat) were stroked over the blanks for 3 seconds at 30 second intervals from one to ten times, and total transferred nickel measured after one, five, and ten touches or wipes; and separately five discrete prepared samples were stroked by the same finger or wipe and total transferred nickel measured. These procedures being repeated three times using five participants for the touches. Total measured nickel transfer by touch or wipe did not differ significantly. Nickel transfer was highest for the pure nickel sample; about 10 times lower and very similar for the Monel alloy 400 (65% Ni, 33% Cu, 2% Fe), copper-nickel (Ni 30%, Cu 70%), and nickel-silver (Ni 18%, Cu 62%, Zn 20%); and about 15 times lower still for stainless steel 316L (Ni 10%, Cr 18%, Mo 3%, Fe 69%). All showed similar relative variation between 1, 5, and 10 touches or wipes on the same sample; and the five touches or wipes on different samples were consistent with transferring five times the amount transferred by one touch or wipe. However, the tests that repeated the touches or wipes on the same sample demonstrated that touches or wipes after the first transferred substantially less material than the

[19] The volar (palmar) aspects of the fingertips (2 cm^2) were sampled.

[20] 22 ng/cm^2 × 60 mins/2 mins = 0.66 µg/cm^2. This should probably be doubled to 1.3 µg/cm^2 for comparison with Lidén *et al.* (2008a) to account for inclusion in the area average of the less exposed parts of the fingers such as the dorsal surfaces.

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

first touch, and were consistent with depositing the same smaller amount of such material at each subsequent touch or wipe.

We found that a simple model that assumed the same constant fraction of the initial transfer occurred with each subsequent wipe or touch for nickel and all the alloys could account for the variation in measured transferred nickel (Figure 2, Figure 3), allowing for the within measurement standard error and 20% variation between measurements.[21] Since an oxide/hydroxide layer forms on nickel within seconds at ambient temperatures (Graham and Cohen, 1972), we interpret this as indicating that the first wipe transferred easily removed material on the oxide/hydroxide surface of the metal or alloy, with subsequent wipes removing the similar (relatively easily removed) oxide/hydroxide surface that re-formed in the 30 second interval between wipes. The same model, with the same wear rate (i.e. fraction of the nickel removed in the first touch or wipe per subsequent touch or wipe), is consistent with the measurements for both touches and wipes, so we use that model in what follows. The estimated wear rate is 0.055 per wipe or touch, so that the wear rate is 0.00183 per second (0.0423/30) of the initial wipe or touch transfer. Implicit in this model is a limitation to a period of less than 1/0.00149 per second = 546 seconds between wiping or touching of the strings, since in that time this simple model predicts that the entire equilibrium surface would have re-formed from the base material.

For example, for pure nickel, the initial oxide/hydroxide layer under ambient conditions is typically 5–10 nm thick (Julander *et al*., 2013), and the initial wipe removed 8.8 µg from the 6.25 cm^2 sample, corresponding to a layer of hydroxide of about 5 nm (density taken as 4.1 g/cm^3 since the top of the surface layer would probably be the hydroxide). The surface oxide/hydroxide layer would re-form in the 30 seconds between wipes at a rate determined by the transfer of electrons and ions through the surface layer, which transfer is impeded by the growing film.[22] While the initial oxide film forms at a high rate within seconds, the rate slows rapidly as the film thickens, so re-forming the film to its limiting thickness is much slower and decreases as the limiting thickness is approached; and in air the hydroxide forms on the surface from the oxide. For this analysis, the approximation to a constant re-formation rate will slightly overestimate total metal removal depending on the pattern of locations and timings of fingers rubbing the strings, since the model assumes a constant rate of renewal of the surface layer rather a rate that slows over time. In this model, to account for the measurements, the nickel alloys would have surface layers with slower electron and ion transport to the surface (e.g. by the inclusion of the other alloying elements or their oxides/hydroxides in the surface layer,[23] or increased equilibrium surface layer thickness); or possibly the surface preparation affects the different alloys to a different extent, so the effective surface area available for removal by rubbing or wiping might have differed. For the stainless steel, the surface layer would be

[21] The model parameters cited are maximum likelihood estimates assuming normally distributed mean estimates at each touch or count number measured.
[22] The transfer mechanism is complex, involving an electric field established across the film driving electron and ion transport, not simple diffusion (Cabrera and Mott, 1949; Ghez 1973; Fehlner and Graham, 2011).
[23] The presence of other alloying elements may change the electric field established across the surface film and the resistance to electron or ion transport.

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

primarily chromic oxide enriched in chromium relative to the composition of the steel – indeed the surface layers of some nickel-containing stainless steels are entirely free of nickel, but can be enriched after suitable heat treatment (Adams, 1983), so the low nickel transfer for stainless steel in Erfani *et al.*'s experiment is unsurprising. The model described here is qualitatively in agreement with the measurements of Staton et al. (2006) (Figure 1), although in that case it appears to have taken one or two rubs before a steady-state condition was reached.

For all except stainless steel, the model estimates of the initial quantity of material removed from the surface by touches or wipes is consistent with expectations – the wipes remove slightly more material than the touches, by between 8.5% (Monel alloy) and 124% (Copper-nickel), perhaps indicating the extra material that can be dissolved, and/or due to the difference in surface roughness of wipes versus fingers. Stainless steel shows the opposite effect, with 35% less removed by wipes, according to the model.

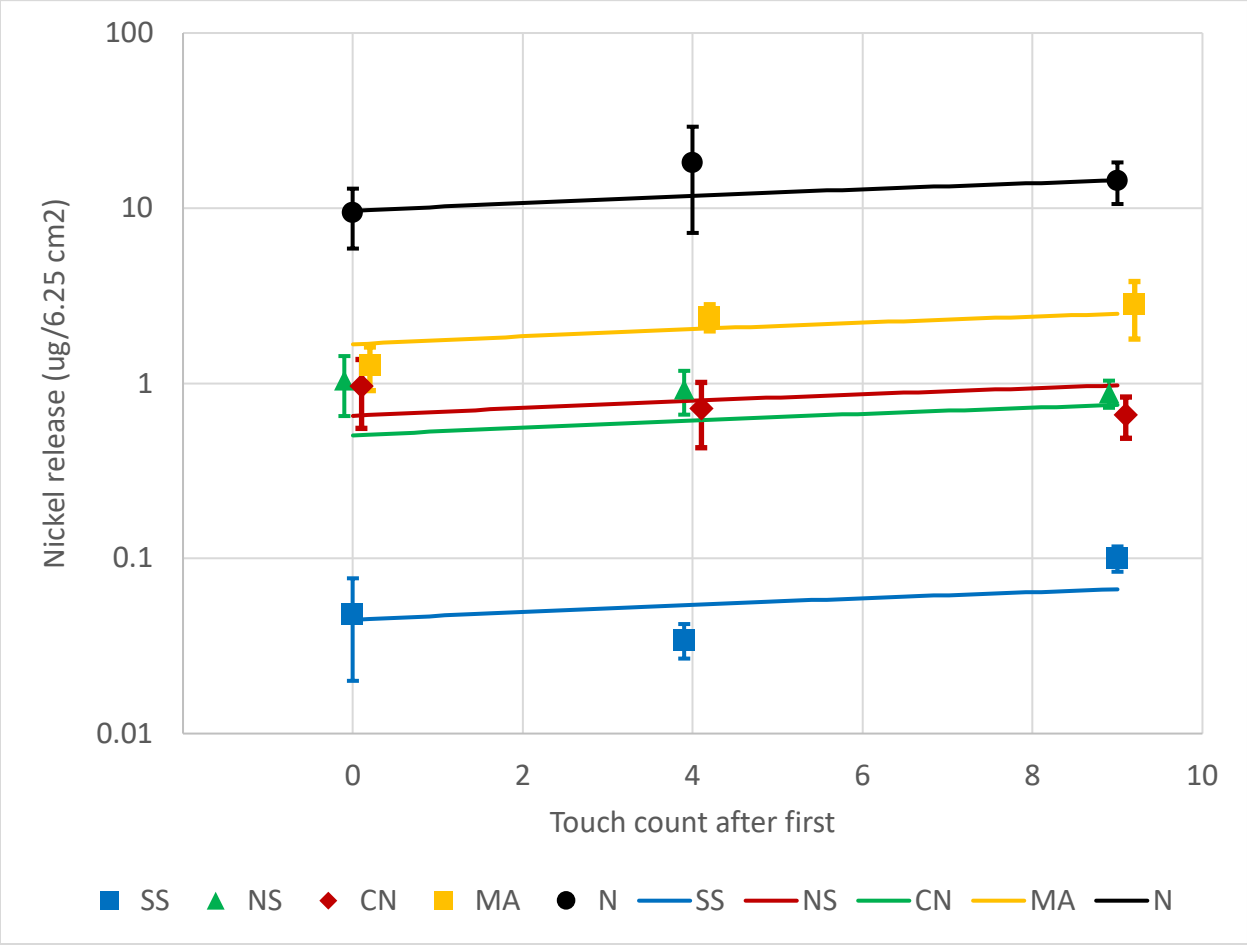

Figure 2 Nickel transfer by touch count measured by Erfani *et al.* (2015). Points are measurements, lines are maximum likelihood model fits (see text). SS: stainless steel; NS: nickel silver; CN: copper nickel; MA: Monel alloy; N: nickel. Error bars are 1 measurement standard error.

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

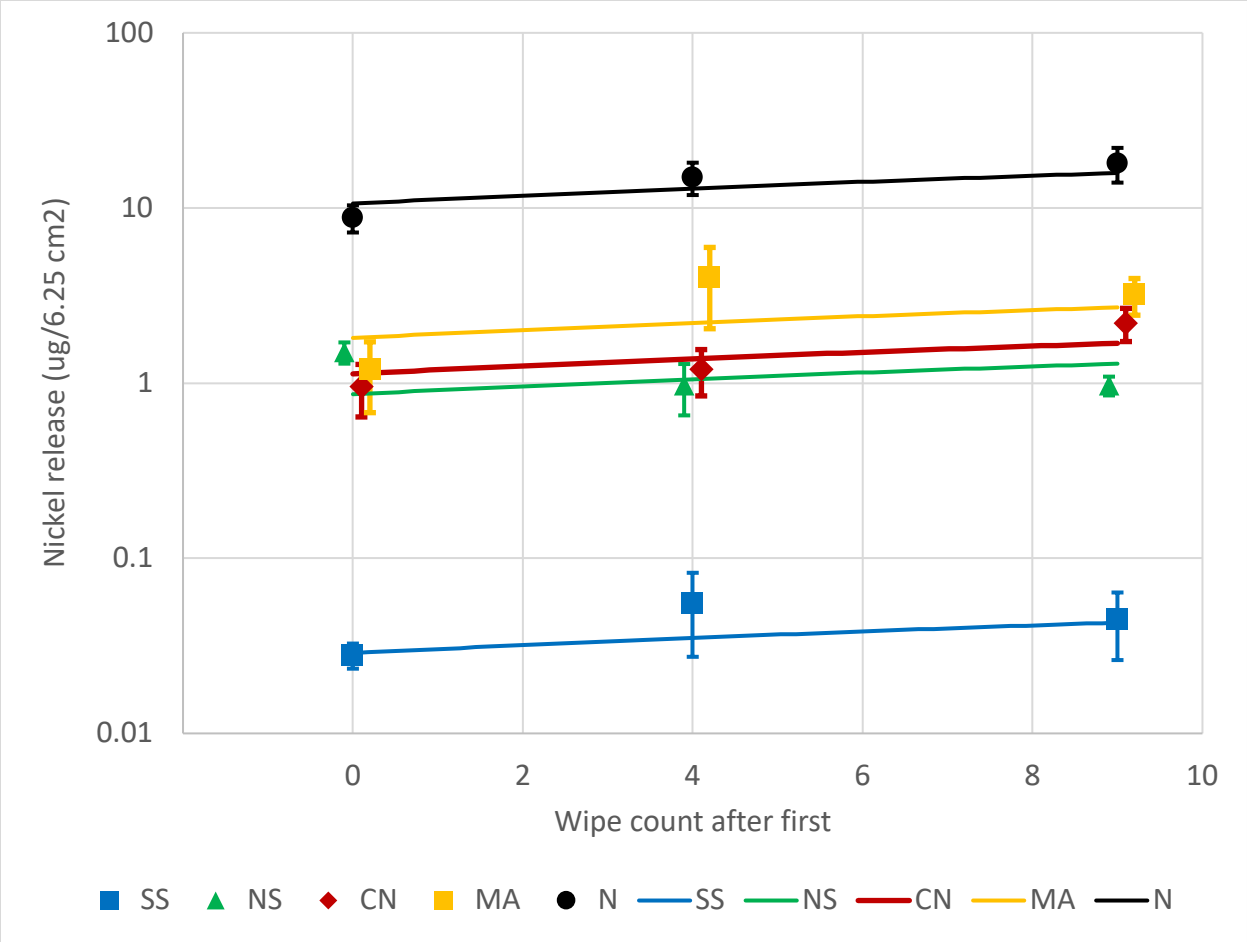

Figure 3 Nickel transfer by wipe count measured by Erfani *et al*. (2015). Points are measurements, lines are maximum likelihood model fits (see text). SS: stainless steel; NS: nickel silver; CN: copper nickel; MA: Monel alloy; N: nickel. Error bars are 1 measurement standard error.

Finally, while prior studies (e.g. Lidén *et al*., 2008b) had measured chromium deposition on hands in various circumstances, Bregnbak *et al*. (2016) studied experimentally the skin deposition of chromium on hands from handling metal (and leather) in such a way as to allow estimation of transfer rates. Bregnbak *et al*. had five participants each manually handle one chromium plated (1.5 µm) metal disc (total surface area 1.8 cm^2) for 30 minutes with the first 3 digits of the right hand (all participants were right handed), and measured the deposition of chromium within delineated 2 cm^2 areas on each digit by wiping, extracting the wipes, and analyzing the resulting fluid.[24] Based on the measured concentrations in the fluid, and taking

[24] The correspondence seen in Erfani *et al*. (2015) between wipe sampling and sampling of similar 2 cm^2 areas on digits justifies our assumption here that this sampling captures practically all the chromium transferred from the discs.

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

account of the relatively high detection limit (two participants had non-detectable transfers on all three digits), the total transfer to all three digits averaged about 0.085 μg.[25]

5.1.2. Application to metal transfer from guitar strings

The measurements obtained from handling of coins or metal objects discussed in Section 5.1.1 show that transfer of metals to fingers occurs quantitatively in proportion to the metal concentration in the surface layer. That layer probably contains a mixture of oxides, hydroxides and metal in variable proportions. There appears to be an outermost layer that is relatively easily removed by rubbing, with subsequent rubbing removing material from the surface layer at the rate that surface layer re-forms. For coins that have been in circulation, readily removable material is distinct in composition from the bulk of the coin material, although for polished coins that presumably lack most of this readily removable material this may change. The alloys of interest for the strings (see Section 5.5 for the ball ends) are primarily stainless steel, lead-free brass, phosphor-bronze, and nickel plating. Lead is a trace impurity in all these string components, while nickel and chromium are either a trace impurity (for brass and phosphor bronze), or part of the bulk material (for nickel plating and stainless steel).

In all cases, the transfer of metals to fingers will depend on the concentration of the metal in the surface layer and the wear rate of that surface layer. For trace impurities, the wear rate will be determined by the wear rate of the whole surface layer. For this evaluation, we make the following assumptions, intended to overestimate potential exposures:

- the surface layer measured by the wipe tests is reformed daily;
- the initial (daily) touch on the strings will remove all of the surface layer measured by the wipe tests;
- for plain (nickel-plated), nickel-plated wrapped, and stainless steel wrapped strings subsequent touches will remove material corresponding to the initial wipe test at the fractional rate that we estimated from the data of Erfani et al. (2015) for nickel and nickel alloy surfaces – see Section 5.1.1 and the discussion below);
- for the brass-wrapped strings
    - lead is present in the wear layers at the upper limit of concentration specified for the brasses (0.05%),
    - nickel and chromium[26] are present in the wear layers in proportion to their concentration relative to lead in the wipe tests,
    - the wear rate of total material is equal to that measured by Fournier and Groves (2003) from polished 2-euro coins – see Table 5 and the discussion below;
- as discussed at the end of Section 3.2, the polymer coating has negligible effect on metal transfer to fingers.

[25] Maximum likelihood estimate assuming the measured concentrations in the fluid were lognormally distributed.

[26] Nickel and chromium impurity levels are not specified for the brasses.

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

The only metal transfer rates for copper/nickel/zinc alloys[27] estimated in Section 5.1.1 where the composition of the surface film was actually measured were initially in the range 0.03 to 0.07 μg/cm^2/sec to three fingers (Table 5, washed and unwashed coins) for total metal content (and similar for extrapolations to 100% content for the individual meals). However, based on the amount of metal removed by polishing, such transfer rates could only continue for a few minutes at most, before the easily transferred (and easily leached) surface materials are depleted. After some polishing, the total metal transfer rates were 0.0012 (2-franc coin) and 0.0067 μg/cm^2/sec (2-euro coin) (Table 5). Other experiments apparently measured rates in the same ranges that depended on the surface conditions of the coins tested, but the surface conditions were not well characterized. For this evaluation, we assume that the brass wrapping on the strings may wear at the same (total metal) rate of 0.0067 μg/cm^2/sec as the polished 2-euro coin, since the string surfaces should correspond most closely to the polished coin surface (see the discussion in Section 5.1.1 of the relative surface concentrations of nickel on the coins versus the strings).

Transfer rates from fresh nickel surfaces measured in available experiments are consistent with the model we developed for the results of Erfani *et al*. (2015), in which the wear rate is apparently controlled by the rate at which fresh surface can form, and that wear rate is 0.00183 per second of the initially removed material for a wide range of alloys. We assume that the 12 wipes applied to each string were performed sufficiently rapidly that little new surface could form within the time taken to perform the wipes, so the initial material wiped from the string represents the same initial value as measured by Erfani *et al*. (2015). This model is applied to the plain (nickel-plated) strings, the nickel-plated wrapping, and the stainless steel wrapping.

For right-handed guitar players,[28] the fingers of the left hand continually hold one or more strings under pressure against the frets (except for rare instances of open-string strumming), while the fingers of the right hand are used to pluck the strings (or use a pick to pluck the strings). The volar surfaces of all ten fingers may thus contact the strings, but palm contact is less frequent and minor (*e.g* for the right hand only when damping all the strings to interrupt playing). The contact is not deliberately rubbing, although fingers of the left hand may rub along the strings when changing chords and the right fingers will rub as the string is plucked. The surface area contacted will be fairly small (smaller than the contact area of fingers with coins), because of the narrowness of the strings. The total length of the strings contacted by the left hand is, on average, probably less than half the scale length (the vibrating length of the string), since it is rare for frets beyond 1/2 the scale length (i.e. the 12th fret) to be reached by the left hand (causing the string to sound more than an octave higher than its open note), while the right hand generally plucks in a length of just an inch or so.

We therefore assume that a player's left-hand fingers could rub off the surface metal (as measured by the wipe tests) on half of each string (since the fingers press the strings only from above) over half the scale length of the instrument, and the right hand all the surface metal on another 2 inches (since the right hand fingers may pluck the strings from one side, and the thumb

[27] The 2-franc coin is pure nickel, but the surface layers of the circulated coins were clearly primarily copper. The 2-euro coin contains copper, nickel and zinc.
[28] For left-handed players, switch left and right here and in what follows.

Crouch@GreenToxiciology.com
Green@GreenToxicology.com

from the other).[29] The highest amounts of initial readily removable lead, nickel, and chromium present on the entire scale length of any string sets in the Redacted line are given in Section 4 as 1.3 µg of lead (on a 5-string bass), 37 µg of nickel (on an 8-string electric guitar), and 13 µg of chromium (on a 5-string bass). Prorating from the wrapped portion of the tested strings (assuming only the wrapped portion contributed to the wipe test results) to the as-strung guitars (taking account of the lengths and the multiple strings of different diameters, including plain and wrapped strings; and the lengths and fraction of each string touched) then gives an initial (first touch) maximum potential daily transfer to fingers of 0.4 µg lead, 12 µg nickel, and 4 µg chromium (for example calculations, see Appendix A: Calculations and examples; all calculations are carried out in the Microsoft® Excel workbook attached to this PDF file (omitted).)

After the first contact with the strings, subsequent playing will rub further material from the strings in proportion to the measured wipe-test results, as described above. Applying this methodology, and assuming an average guitar player plays for 1.5 hours/day (see e.g. https://hubguitar.com/articles/how-long-does-it-take-to-learn-guitar)[30] the additional maximum potential transfers to fingers are 4.0 µg/day lead, 121 µg/day nickel, and 40 µg/day chromium; and the maximum total sums of the initial and subsequent potential transfers are 4.4 µg/day lead, 133 µg/day nickel, and 45 µg/day chromium. The maximum transfers to just the right hand are 0.82 µg/day lead, 32 µg/day nickel, and 8.3 µg/day chromium, or 19 to 24% of the total. Note that the maxima for the initial and subsequent transfers do not necessarily sum to the maxima for the total transfer, because different string sets may be involved in each case; and the maxima for the right hand for each of lead, nickel, and chromium are different fractions of the totals since each is due to different string sets than the totals.

5.2. Ingestion exposure to lead, nickel, and chromium from guitar strings

Lead transferred to fingers may be absorbed by hand-to-mouth transfer and subsequent ingestion. The hand-to-mouth exposure discussion of the OEHHA (2011) discusses various values for the potential contact area for each hand-to-mouth contact, with a range of 10 to 20 cm^2, the upper end corresponding to about the area of one side of one finger of an adult.

[29] Since the scale length varies for different instruments, this implies that the fraction of the total metal transferred to the right hand varies with the instrument.

[30] The only research measuring the time spent playing instruments appears to be for music students. The most detailed published data (microdata) from the American Time Use Survey (https://www.bls.gov/tus/) of the U.S. general population combines time listening to and playing music for which the average daily time (ages 15+) from 2003 to 2022 (omitting 2020, when the survey was suspended for several months) was 1.44 hours/day among those who reported listening to or playing music. Hallam et al. (2012) reported that the average weekly time playing a main instrument increased with examination grade in the English system of music education for beginners, reaching 1.0 hour/day at the highest level when students would be admissible to conservatoires or to music study at colleges. Hallam et al. (2018) reported that in the same group of beginners, guitar players averaged from 0.27 hours/day at ages 7–10 to 0.87 hours/day at ages 15+. Jørgensen (2002) measured times averaging 2.4 to 2.9 hours/day on their main instrument for students at Norwegian conservatoires, while Lammers and Kruger (2006) showed an average practice time of 0.9 hours/day among music education students at five U.S. institutions — three Schools of Music at public Universities and two Liberal Arts Colleges.

Crouch@GreenToxiciology.com
Green@GreenToxicology.com

For an average guitar player, the most contaminated area of the hand will be the volar surfaces of fingers (including the thumb); and such a player may occasionally lick those surfaces (*e.g.* in order to aide in turning of pages of music). The frequency of such licking is irrelevant (provided it is high enough), since the rate-limiting step is contact with the guitar strings (see Section 5.1.2). For the purposes of this evaluation, therefore, it is assumed that a guitar player may lick the contaminated surface of one finger (the same finger each time), and hence potentially ingest the entire metal content on that finger. The right hand[31] fingers will pluck the string from both sides, but one side of the strings is plucked only by the thumb, with the other side of the strings plucked by fingers, so the thumb will be exposed to 1/2 the total material transferred to the right hand, or 9 to 12% (depending on the instrument scale length, see footnote 29) of the total transferred to both hands. With the assumptions made above, the left hand is the most heavily contaminated (about 76 to 81% of the total, again depending on the instrument scale length) since it contacts a greater area of the strings; but each finger will be contaminated with approximately 1/5 of the total on that hand, or 15 to 16% of the total material transferred. It is more likely that a right-hand finger will be the one licked and used to turn the pages of music, since the left hand will at that time be used to hold the guitar in place. Nevertheless, as a conservative assumption we assume that 15 to 16% of the total material transferred from the strings is placed into contact with the mouth.

OEHHA (2011) has as a default assumption that 50% of lead brought into contact with the mouth will be ingested. This is based primarily on the study, characterized as the best available at that date (2011), of Camann et al. (2000), measuring the fraction of three pesticides removed from the hands of three adult volunteers by gauze wipes moistened with human saliva. Since then, the study of Sahmel et al. (2015) has demonstrated a transfer efficiency from lead-contaminated fingers to human saliva of 24% at a total hand lead loading that is similar to the total loading of all three metals considered here. We here adopt this updated and more relevant estimate, which we assume corresponds to the ingestion efficiency of all the finger-borne metals. The total ingestion rates then correspond to 0.17 µg/day lead, 4.9 µg/day nickel, and 1.7 µg/day chromium.

OEHHA (2011) also suggests that up to 25% of lead contamination on hands could be ingested via transfer to food eaten by a person after using the product at issue. However, an average guitar player would be likely to wash his or her hands prior to eating, based on survey information on adults (Haston et al., 2020), so this route of exposure is unlikely for the average user of Redacted strings, and is not considered further.

5.3. Dermal absorption exposure of lead, nickel, and chromium from guitar strings

5.3.1. Lead

Dermal absorption of lead transferred to the surface of the skin has been observed for some chemical forms of lead. Stauber *et al.* (1994) reported such absorption for lead, lead oxide, lead acetate, and lead nitrate. A quantitative estimate of 29.5% dermal absorption (measured as the loss from the applied material) was obtained for lead nitrate applied under extreme conditions

[31] Again, for left-handed players, switch left and right here and in what follows.

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

(24 hours occlusive contact with the forearm), but no quantitative estimates were obtained for the other chemical forms.

The chemical forms of corrosion due to synthetic sweat of alloys of Cu, Ni, and Zn was investigated by Colin *et al*. (1999). They observed that the surface corrosion layers were composed primarily of copper and nickel products, primarily oxides and hydroxides with minor chlorine-based compounds. The relevant form of lead rubbed from the similar alloys at issue here is thus likely to be metallic lead or lead oxide.

Filon *et al*. (2006) measured *in vitro* dermal penetration by lead oxide using human skin samples. After 24 hours application of 5 mg/cm^2 of lead oxide in synthetic sweat, penetration through intact skin was less than 0.2% of the applied lead oxide. At the end of the experiment, the skin itself (after mild rinsing) retained about 17% of the applied lead oxide, although other experiments (of shorter duration) indicated that washing with soap removed most of this (<2% of the applied lead oxide remained after washing with soap after a 30-minute application). It is likely that most of the lead retained in the skin even after the 24-hour application was in the surface layer and would have been readily removed by washing with soap. For example, Sun *et al*. (2002) demonstrated using tape stripping that even 12 hours after last exposure and after hand washing with soap followed by ethanol cleaning, approximately 1/3rd to 1/2th of the lead remaining in the exposed (dorsal hand) skin of heavily exposed battery workers was in the upper two of ten skin layers, which is about a two- to four-fold excess compared with what would be expected from a linear gradient through the skin. Thus even after extensive washing of the surface, a fraction of the lead in skin was still in the surface layer. If in the Filon *et al*. (2006) experiment it is assumed that only the applied lead oxide that entered the skin is relevant to absorption, then absorption of lead oxide would be about 2% (*i.e.* of the lead entering the skin, about 2% was absorbed over the 24 hours of the experiment).

Sun *et al*. (2002) also demonstrated that in rats, lead absorption through the skin (as measured by urinary excretion) varied with chemical form, with absorption rates in the order lead naphthenate > lead nitrate > lead stearate > lead sulfate > lead oxide > lead powder. Compared with lead nitrate, lead oxide dermal absorption in rats was 15.7% and lead powder 6.5%. Applying the relative absorption observed in Sun *et al*. (2002) in rats to the 29.5% maximum absorption seen in 24 hours for lead nitrate by Filon *et al*. (2006) in humans gives estimates of 4.6% absorption for lead oxide, and 1.9% for metallic lead, assuming 24-hour application with no washing.

As an upper bound, it is thus assumed that dermal absorption of the lead rubbed from guitar strings might be as high as 4.6%, leading to an overestimate of approximately 0.20 μg/day.

5.3.2. Nickel

In vitro penetration of soluble nickel salts through the stratum corneum of human skin was measured by Tanojo et al. (2001) using a 1% water solution of the salt in a continuous flow-through diffusion cell. In 96 hours, between 0.02 and 1.09% had permeated through, and between 0.1 and 0.95% was retained in the stratum corneum.

Hostynek et al. (2001) examined the *in vivo* distribution of nickel on the surface and throughout the stratum corneum by tape stripping after application of soluble nickel salts (applied dissolved

Crouch@GreenToxiciology.com
Green@GreenToxicology.com

in methanol and dried in place on the skin) for periods of up to 25 hours. The fraction remaining on the surface (determined by swabbing with water-moistened wipes) after 24 hours ranged from 28% to 94% depending on the salt and skin location. Most of the remainder was deposited in the stratum corneum, with concentrations increasing with application period and decreasing with depth to practically non-detectable at 3/4th of the thickness of the stratum corneum.

Larese et al. (2007) demonstrated that metallic nickel powder dispersed (at 5 g per 100 mL) in artificial sweat at pH 6.5 would produce ionic nickel (at 27.1 mg/L) in solution that diffused through human skin *in vitro* over 24 hours, measuring a lag time of 14 hours and a permeation coefficient of 6.1×10^{-4} cm/hr.

Moody et al. (2009) measured *in vitro* dermal absorption of ^{63}Ni (half-life of 100.1 years) in spiked soil suspensions in water or in acetone, using human skin in flow-through diffusion cells for 24 hours. Total transmission of nickel through the skin was 0.5% from the spiked soil suspension in water, and 1.8% from the neat acetone. Recovery from the skin itself after soap washing was 0.5% for the spiked soil suspension, and 20.9% from the neat acetone.

Given Larese and colleagues' (2007) demonstration, it is prudent to assume that the nickel oxide/hydroxide deposited on the skin would dissolve to some extent in skin surface liquids and penetrate the skin to some extent. Most of the material would not dissolve and would be removed by washing; as demonstrated by Hostynek et al. (2001), after 24 hours 28% to 94% even of soluble nickel compounds were removed by washing, and 89% or 90% after 30 minutes. Further, playing for the 1.5 hours/day assumed would result in skin thickening (calluses) on the fingers contacting the strings, particularly on the right hand if no pick is used, so that the published studies, which relied on non-callused skin, may overestimate penetration for guitar players' fingers. As an upper bound, we assume that 2% of the total loading of nickel may ultimately penetrate, as shown by Tanojo et al. (2001) for soluble nickel compounds (using the sum of the fraction penetrating and retained in the stratum corneum), or 2.7 μg/day.

5.3.3. Chromium

Gammelgaard et al. (1992) examined permeation of potassium dichromate (Cr(VI)), chromium trichloride hexahydrate (Cr(III)), and chromium nitrate nonahydrate (Cr(III)) at pH 5.0 through human skin *in vitro*. They found that permeation of the Cr(III) compounds was undetectable after 190 hours, while some potassium dichromate was detectable. Deposition in the skin of Cr (III) compounds was about 10% or less of that of potassium dichromate (with deposition in the dermis about 10% or less of that in the epidermis in both cases).

Van Lierde et al (2006) found similar results to Gammelgaard et al. (1992) — they were unable to detect any chromium (III) permeation through thin surface skin membranes of either porcine or human origin after 168 hours from simulated sweat solution at pH 5.5, whereas chromium (VI) did permeate.

Larese et al. (2007) demonstrated that a suspension of chromium in synthetic sweat at pH 6.5 permeates through skin to a lesser extent than nickel from nickel suspension — in fact even in the suspension it was impossible to measure any chromium ion, and the chromium permeation was so low that it was impossible to measure a flux and lag time over the 24 hours measured.

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

The same experiment performed on a Cr(VI) solution (potassium dichromate) at pH 6.5 showed a measurable permeation rate with lag time of 12.5 hours and permeation rate 4 times lower than nickel from the nickel suspension. Subsequent experiments using the same powdered chromium suspended in synthetic sweat with pH of 3.5, 4.5, and 5.5 ([Larese] Filon et al., 2008) showed increasing ion concentration with decreasing pH, and a permeation experiment at pH 4.5 demonstrated a lag time of 1.1 hour and a permeation flux about 9 times lower than potassium dichromate at pH 6.5.

Based on these experiments, the chromium (III) oxides/hydroxides deposited on skin (average pH about 5.1, Lambers et al., 2006) from guitar strings would permeate skin only to an extent insignificant for assessments of potential exposure. We therefore ignore dermal absorption of chromium.

5.4. Total exposure to lead, nickel, and chromium from guitar strings

Summing ingestion and dermal exposures, total exposure from Redacted guitar strings would be less than 0.37 µg/day lead, 7.5 µg/day nickel, and 1.7 µg/day chromium (Table 9)

Table 9 Summary of ingestion, dermal, and total exposures

	Chromium	Lead	Nickel	
Total transfer to hands	44.5	4.39	133.5	µg/day
Left-hand fraction	81.4%	81.4%	76.1%	of total
Each finger	16.3%	16.3%	15.2%	of total
Ingestion fraction	24%	24%	24%	of amount on finger
Total ingestion	1.74	0.17	4.88	µg/day
Dermal absorption fraction	0.0%	4.6%	2.0%	of total
Dermal absorption	0.00	0.20	2.67	µg/day
Total exposure	1.74	0.37	7.55	µg/day

The overestimate for lead is below the MADL level of 0.5 µg/day, and *ipso-facto* lower than the NSRL of 15 µg/day, even without taking account of averaging over non-playing days. The nickel exposure is to total nickel, but the majority (65%) is from the hand-to-mouth exposure to nickel oxide/hydroxide, of which only a small fraction is likely to be solubilized by saliva. However, even the total nickel exposure corresponds to 0.13 µg/kg-day,[32] so 1,000 times this amount is 0.13 mg/kg-day, which is well below the lowest NOEL of 1.12 mg/kg-day (Section 2.2) for soluble nickel. The chromium exposure is entirely to chromium III, so there is no requirement for any Proposition 65 warning in any case; and this exposure is well below even the MADL for chromium VI of 8.2 µg/day (Section 2.3).

[32] Using a human body weight of 58 kg, see Section 2.4.

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

5.5. Ball-ends on Redacted guitar strings

The ball-ends are brass cylinders with axial holes with dimensions given in Section 3.1. They are constructed of brass containing 1.6 to 3.5% lead, 0.3% nickel, and are unspecified as to chromium which would be a trace contaminant. The ball-end holds the bridge end of the string by engagement of the ball-end in a slot, by pulling the string through a hole too small for the ball-end,[33] by pinning the ball-end within a hole in the bridge,[34] or by similar means. The ball-end is not accessible once the guitar is strung.

During installation of the string, it is possible that the user may have momentary contact with the ball-end (*e.g.* while removing the string from the package), but there is no need for any such contact. No stringing operation requires touching the ball-end, and stringing is most efficiently accomplished without touching the ball-end — the ball-end of the string is moved by holding the string in order to manipulate the string and ball-end into the required configuration (the videos referenced in Footnotes 33 and 34 clearly show this).

To overestimate the potential exposure from contact with the ball-end during stringing, we here assume contact equivalent to handling during counting of coins (Table 3), pro-rated for the relative exposed surface areas of ball-end and coin, and using the highest metal transfer rate measured with coins (for 2-euro coins). Table 10 shows the worst-case estimates for total metal transfer per ball end. The worst-case wipe-test ratio of chromium to nickel from the brass-wrapped strings is 0.78, and we use this as a best estimate for an upper bound on the chromium content of the brass in the ball ends, giving an estimate of 0.235%. A conservative estimate of potential exposure then results from stringing all 12 strings of a 12-string guitar, with 7 small ball-ends and 5 large ball ends (see Table 1), which gives a total transfer to fingers of 0.066 µg lead, 0.0056 µg nickel, and 0.0044 µg chromium. These are respectively only 1.5%, 0.004%, and 0.01% of the daily transfers to hands from the strings (Section 5.1.2), so clearly have no effect on the conclusions reached above, even if re-stringing were performed daily.

[33] On electric guitars. See for example, the video at http://www.dummies.com/how-to/content/how-to-string-an-electric-guitar.html.
[34] On acoustic guitars. See for example the video at https://www.youtube.com/watch?v=qXaMn4jkxDM.

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

Table 10 Estimated maximum lead exposure from contact with ball-ends

Coins			
	2-franc	2-euro	
Maximum total metal transfer (Table 3)	0.96	1.89	µg
Coin facial surface area (Section 5.1.1)	11.00	10.42	cm^2
Total metal transfer/unit surface area	0.087	0.18	µg /cm^2
Guitar ball-ends			
	Large	Small	
Surface area	1.31	0.55	cm^2
Total metal transfer (using 0.18 µg /cm^2)	0.24	0.10	µg

6. Conclusion

Our initial, highly conservative examination of exposure to lead, nickel, and chromium from guitar strings — which assumed that guitar players *licked* their strings — sufficed to indicate that such exposure would yield doses that were unlikely to exceed the MADL (hence also the NSRL) for lead; and that would amount to 1,000 times less than the NOEL for nickel. Chromium exposure from guitar strings would all be in the III oxidation state, so irrelevant for Proposition 65; but even if it were in the form of chromium VI, such exposure would not exceed the MADL.

Our more detailed and realistic examination of potential pathways of exposure via guitar playing confirms that an average user of Redacted guitar strings would have intakes of lead, nickel, and chromium that are too small to trigger any requirement for a warning under Proposition 65.

7. References

Adams RO. A review of the stainless steel surface. Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films. 1983 Jan 1;1(1):12–18. http://dx.doi.org/10.1116/1.572301.

Bregnbak D, Thyssen JP, Jellesen MS, Zachariae C, Johansen JD. Experimental skin deposition of chromium on the hands following handling of samples of leather and metal. Contact Dermatitis. 2016 Aug;75(2):89–95. https://doi.org/10.1111/cod.12605.

Cabrera NF, Mott NF. Theory of the oxidation of metals. Reports on Progress in Physics. 1949;12(1):163–184. https://doi.org/10.1088/0034-4885/12/1/308.

Camann DE, Mjundar TK, Geno PW. 2000. Evaluation of Saliva and Artificial Salivary Fluids for Removal of Pesticide Residues from Human Skin. EPA/600/R-00/041. (PB2000-105542). https://ntrl.ntis.gov/NTRL/dashboard/searchResults/titleDetail/PB2000105542.xhtml.

Crouch@GreenToxiciology.com
Green@GreenToxicology.com

Colin S, Beche E, Berjoan R, Jolibois H, Chambaudet A. An XPS and AES study of the free corrosion of Cu-, Ni- and Zn-based alloys in synthetic sweat. Corrosion Sci. 1999;41(6):1051–1065. https://doi.org/10.1016/S0010-938X(98)00141-3.

EFSA, 2015. Scientific Opinion on the risks to public health related to the presence of nickel in food and drinking water. EFSA Journal. 2015;13(2)4002. https://doi.org/10.2903/j.efsa.2015.4002.

Erfani B, Lidén C, Midander K. Short and frequent skin contact with nickel. Contact Dermatitis. 2015 Oct;73(4):222–230. https://doi.org/10.1111/cod.12426.

Filon FL, Boeniger M, Maina G, Adami G, Spinelli P, Damian A. Skin absorption of inorganic lead (PbO) and the effect of skin cleansers. J. Occup Environ. Med. 2006;48(7):692–692. https://www.jstor.org/stable/45009244.

Filon FL, D'Agostin F, Crosera M, Adami G, Bovenzi M, Maina G. In vitro percutaneous absorption of chromium powder and the effect of skin cleanser. Toxicology in Vitro. 2008 Sep 1;22(6):1562–1567. https://doi.org/10.1016/j.tiv.2008.06.006.

Fehlner, FP, Graham MJ. Thin Oxide Film Formation on Metals. Ch. 4 in: Marcus P (ed.), *Corrosion Mechanisms in Theory and Practice, 3rd Edition*. CRC Press, 2011. ISBN 9780429143564. https://doi.org/10.1201/b11020.

Fournier PG, Govers TR, Fournier J, Abani M. Contamination par le nickel et d'autres métaux lors de la manipulation des pièces de monnaie–comparaison entre francs français et euros. Comptes Rendus Physique. 2002 Jan 1;3(6):749–758. https://doi.org/10.1016/S1631-0705(02)01371-3.

Fournier P-G, Govers TR. Contamination by nickel, copper and zinc during the handling of euro coins. Contact Dermatitis 2003;48(4):181–188. https://doi.org/10.1034/j.1600-0536.2003.00028.x.

Gammelgaard B, Fullerton A, Avnstorp C, Menné T. Permeation of chromium salts through human skin in vitro. Contact Dermatitis. 1992 May;27(5):302–310. https://doi.org/10.1111/j.1600-0536.1992.tb03284.x.

Ghez R. On the Mott-Cabrera oxidation rate equation and the inverse-logarithmic law. The Journal of Chemical Physics. 1973 Mar 1;58(5):1838–1843. https://doi.org/10.1063/1.1679440.

Graham MJ, Cohen M. On the mechanism of low-temperature oxidation (23–450 C) of polycrystalline nickel. Journal of the Electrochemical Society. 1972 Jul 1;119(7):879–881. https://doi.org/10.1149/1.2404360.

Gwozdz R, Grass F. Contamination by human fingers: The Midas touch. J. Radioanal. Nucl. Chem. 2004;259(1):173–176. https://doi.org/10.1023/b:jrnc.0000015824.18586.42.

Hallam S, Creech A, Varvarigou M. Are there differences in practicing and motivation between beginners playing different musical instruments?. Orfeu, Florianópolis, 2018;3(1)54–84. https://doi.org/10.5965/2525530403012018054.

Crouch@GreenToxiciology.com
Green@GreenToxicology.com

Hallam S, Rinta T, Varvarigou M, Creech A, Papageorgi I, Gomes T, Lanipekun J. The development of practising strategies in young people. Psychology of Music. 2012;40(5): 652–680. https://doi.org/10.1177/0305735612443868.

Haston JC, Miller GF, Berendes D, Andújar A, Marshall B, Cope J, Hunter CM, Robinson BM, Hill VR, Garcia-Williams AG. Characteristics associated with adults remembering to wash hands in multiple situations before and during the COVID-19 pandemic—United States, October 2019 and June 2020. Morbidity and Mortality Weekly Report. 2020 Oct 10;69(40):1443–1449. https://doi.org/10.15585/mmwr.mm6940a2.

Hostýnek JJ, Dreher F, Nakada T, Schwindt D, Anigbogu A, Maibach HI. Human stratum corneum adsorption of nickel salts. Acta Dermato-Venereologica. 2001;(Suppl 212):11–18. https://doi.org/10.1080/000155501753279587.

Institute of Medicine. 2001. Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Manganese, Molybdenum, Nickel, Silicon, Vanadium, and Zinc. Washington, DC: The National Academies Press. https://doi.org/10.17226/10026.

Institute of Medicine. 2006. Dietary Reference Intakes: The Essential Guide to Nutrient Requirements. Washington, DC: The National Academies Press. https://doi.org/10.17226/11537.

Jørgensen H. Instrumental performance expertise and amount of practice among instrumental students in a conservatoire. Music Education Research. 2002 Mar 1;4(1):105–119. https://doi.org/10.1080/14613800220119804.

Lambers H, Piessens S, Bloem A, Pronk H, Finkel P. Natural skin surface pH is on average below 5, which is beneficial for its resident flora. International Journal of Cosmetic Science. 2006 Oct;28(5):359–370. https://doi.org/10.1111/j.1467-2494.2006.00344.x.

Lammers M, Kruger M. Brass and woodwind student practice habits in Norway, Japan, and the United States. National Association of College Wind and Percussion Instructors Journal. 2006;54(4):4–13.

Larese F, Gianpietro A, Venier M, Maina G, Renzi N. In vitro percutaneous absorption of metal compounds. Toxicology Letters. 2007 Apr 5;170(1):49–56. https://doi.org/10.1016/j.toxlet.2007.02.009.

Lidén C, Skare L, Vahter M.. Release of nickel from coins and deposition onto skin from coin handling — comparing euro coins and SEK. Contact Dermatitis. 2008a;59(1):31–37. https://doi.org/10.1111/j.1600-0536.2008.01363.x.

Lidén C, Skare L, Nise G, Vahter M. Deposition of nickel, chromium, and cobalt on the skin in some occupations–assessment by acid wipe sampling. Contact Dermatitis. 2008b Jun;58(6):347–354. https://doi.org/10.1111/j.1600-0536.2008.01326.x.

Moody RP, Joncas J, Richardson M, Petrovic S, Chu I. Contaminated soils (II): in vitro dermal absorption of nickel (Ni-63) and mercury (Hg-203) in human skin. Journal of Toxicology and Environmental Health, Part A. 2009 Mar 16;72(8):551–559. https://doi.org/10.1080/15287390802706322.

Nielsen FH. 2012. Manganese, Molybdenum, Boron, Chromium, And Other Trace Elements. Ch. 38 in *Present Knowledge in Nutrition, 10th Edn*., Erdman JW, Macdonald IA, Zeisel SH (eds.), ILSI & Wiley-BlackWell. https://doi.org/10.1002/9781119946045.ch38.

Nielsen F. Nickel. Advances in Nutrition. 2021 Jan;12(1):281-282. https://doi.org/10.1093/advances/nmaa154.

NiPERA (2000a). A One-Generation Reproduction Range-Finding Study in Rats with Nickel Sulfate Hexahydrate, Study No. 3472.1. Final Report. 12/28/00 Springborn Laboratories, Inc. Spencerville, OH 45887, sponsored by the Nickel Producers Environmental Research Association (NiPERA), Durham, NC. Available from https://nickelinstitute.org/media/4869/sli-springborn-laboratories-inc-2000a-copyright.pdf.

NiPERA (2000b). An Oral (Gavage) Two-Generation Reproduction Toxicity Study in Sprague-Dawley Rats with Nickel Sulfate Hexahydrate, Study No. 3472.2. Final Report. 12/22/00. Springborn Laboratories, Inc. Spencerville, OH, sponsored by the Nickel Producers Environmental Research Association (NiPERA), Durham, NC. Available from https://nickelinstitute.org/media/4870/sli-springborn-laboratories-inc-2000b-copyright.pdf.

OEHHA, 2011. Proposition 65 Interpretive Guideline No. 2011-001. Guideline for Hand-to-Mouth Transfer of Lead through Exposure to Consumer Products. May 2011. Available at https://oehha.ca.gov/proposition-65/crnr/release-final-interpretive-guideline-no-2011-001-hand-mouth-transfer-lead.

OEHHA, 2012. Nickel Reference Exposure Levels. February 2012. Available at https://oehha.ca.gov/media/downloads/crnr/032312nirelfinal.pdf.

OEHHA, 2019. Proposition 65 Definition of Nickel (Soluble Compounds). Available at https://oehha.ca.gov/proposition-65/crnr/proposition-65-definition-nickel-soluble-compounds.

Sahmel J, Hsu EI, Avens HJ, Beckett EM, Devlin KD. Estimation of hand-to-mouth transfer efficiency of lead. Annals of Occupational Hygiene. 2015 Mar 1;59(2):210–220. https://doi.org/10.1093/annhyg/meu088.

Smith VH, Charles-Holmes R, Bedlow A. Contact dermatitis in guitar players. Clin. Exp. Dermatol. 2006;31(1):143–145. https://doi.org/10.1111/j.1365-2230.2005.01943.x.

Staton I, Ma R, Evans N, Hutchinson RW, McLeod CW, Gawkrodger DJ. Dermal nickel exposure associated with coin handling and in various occupational settings: assessment using a newly developed finger immersion method. Br. J. Dermatol. 2006;154(4):658–664. https://doi.org/10.1111/j.1365-2133.2006.07128.x.

Stauber JL, Florence TM, Gulson BL, Dale LS. Percutaneous absorption of inorganic lead compounds. Sci. Total Environ. 1994;145(1–2):55–70. https://doi.org/10.1016/0048-9697(94)90297-6.

Sun C-C, Wong T-T, Hwang Y-H, Jee S-H, Wang J-D. Percutaneous absorption of inorganic lead compounds. AIHA J. 2002;63(5):641–646. https://doi.org/10.1080/15428110208984751.

Crouch@GreenToxiciology.com
Green@GreenToxicology.com

Sung K, Chang J, Freivalds A, Kong YK. Development of the two-dimensional biomechanical hand model for a guitar player. Proceedings of the Human Factors and Ergonomics Society Annual Meeting. 2013 Sep;57(1):1653–1657. https://doi.org/10.1177/1541931213571367.

Tanojo H, Hostýnek JJ, Mountford HS, Maibach HI. In vitro permeation of nickel salts through human stratum corneum. Acta Dermato-Venereologica. 2001;81(Suppl 212):19–23. https://doi.org/10.1080/000155501753279596.

Van Lierde V, Chéry CC, Roche N, Monstrey S, Moens L, Vanhaecke F. In vitro permeation of chromium species through porcine and human skin as determined by capillary electrophoresis–inductively coupled plasma–sector field mass spectrometry. Analytical and Bioanalytical Chemistry. 2006 Jan;384:378–384. https://doi.org/10.1007/s00216-005-0226-z.

Crouch@GreenToxiciology.com
Green@GreenToxicology.com

Appendix A: Calculations and examples

All the following calculations are performed in the Microsoft® Excel workbook attached to this PDF file (omitted). The sheet "Data" calculates results for every Redacted string set, and selects the maximum potential exposure from any such string set, using the methodology discussed in Sections 5.1.2 and 5.2. Sheet "Ball-ends" shows the calculation of exposure from ball ends (Section 5.5). The workbook also incorporates, in the other sheets, the analyses of literature and other calculations discussed in Section 5.1.1.

Each Redacted guitar string is one of nine types, depending on:

- Coating: Redacted
- Surface material: Redacted
- Instrument type: Redacted

Not all combinations are represented, so that an unambiguous list of the nine combinations may be abbreviated by (N_B, P_B, N_Z, O_N, N_N, P_N, N_NB, N_SB, U_N) where the first letter of each entry represents the coating, the second the surface material, and the third (where present) the instrument type. This is the named Code_list in the attached workbook. The first three combinations correspond to the wrapped and coated strings in the acoustic guitar string sets, the next three to the wrapped and coated strings in the electric guitar string sets, the next two to wrapped and coated strings in bass guitar string sets, and the last to the plain strings (with uncoated, nickel-plated surfaces) all except bass sets. There is also one (acoustic) bass string set of type N_Z. One string of each type, the largest gauge[35] used in any string set, was tested in the wipe tests.

East string set is characterized by a number of plain strings (code U_S) with varying gauges (diameters, in inches) and a number of wrapped, coated strings of the same coating and surface material type but differing gauge.[36] All strings of 0.022 gauge or less are plain, those above 0.022 gauge are wrapped and coated.

String sets are designed for acoustic guitars, electric guitars, 4-string bass guitars, and 5-string bass guitars. We assume that the scale lengths (the maximum vibrating length of the strings, between the nut and the bridge) of these guitars are typically 26, 25.5, 34, and 35 inches respectively (https://en.wikipedia.org/wiki/Scale_length_(string_instruments)).

The tested strings were wiped over their full (as-sold) length, which includes the ball end and, for the wrapped, coated strings, some length of unwrapped, uncoated core. However, the results of the wipe tests are attributed here to the wrapped, coated portion of the strings, which were (nominally) 39.25 inches long for the bass strings, 41.125 inches long for the plain string, and 33.5 inches long for all the others.

[35] One exception — the 5-string bass string set Part No. Redacted has a maximum gauge slightly larger (0.135) than the tested string (0.13).

[36] The 12-string sets have duplicates of some gauges.

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

To estimate the quantities of surface metals transferred to fingers on first touch of the strings, the wipe test result is pro-rated from the surface area of the wrapped, coated section of the tested string (or the total surface area of the tested plain string) to the surface area that could be touched by the fingers on a strung guitar. For the left hand, that is assumed to be 1/2 the scale length, with just one side of the all the strings touched, so overall 1/4 of the surface area of the strings on a strung guitar. Similarly, for the right hand, the wipe test results are pro-rated from the surface area of the tested string to the surface area of 2 inches of the strings on a strung guitar, with the assumption that the right hand could touch the whole surface of the strings. These calculations are performed separately for the plain strings and the wrapped, coated strings of the set, and the results added to obtain the total.

The same calculations are performed for each string set in the Redacted line, and the worst-case (highest transfer of metal) selected separately for each of lead, nickel, and chromium.

For example, for a 5-string bass set (Part No. Redacted, type N_SB). the five strings (all wrapped and coated) have diameters Redacted inches, and the typical scale length is 35 inches (see above), giving a total surface area of the strings in the scale length of 308.6 cm^2, so that the left hand touch area (half of each string over half the scale length) is 77.1 cm^2; and the right hand's touch area (2 inches, total area of each string) is 17.6 cm^2 for a total of 94.8 cm^2. The tested string had a diameter of 0.13 inches, and a wrapped length of 39.25 inches, for a wrapped surface area of 103.4 cm^2. Attributing the total wipe measurement of 0.44 µg lead to the wrapped portion of the tested string, the amount potentially transferrable to the player's fingers is (94.8/103.4)*0.44 = 0.4 µg, which is assumed to occur daily. In this case (which turns out to be the worst-case for lead), there are no plain strings in the set, so no separate calculation for the plain strings is necessary; for string sets with plain strings, the same calculation is repeated for both plain and wrapped strings and the two results added. Similar calculations are repeated for nickel and chromium.

Estimation of the subsequent transfer to fingers after the first touch is done slightly differently for the cases of brass and phosphor bronze wrapped strings versus nickel-plated and stainless steel wrapped and plain (nickel-plated) strings. For the brass and phosphor bronze wrapped strings, the total metal removal rate found for polished 2-euro coins by Fournier and Groves (2013) of 0.0067 µg/cm^2/sec (Table 5) is applied to the total surface area of the wrapped strings rubbed by the fingers, and, for lead, multiplied by the upper limit of 0.05% lead content in the brass or phosphor bronze to obtain the rate of transfer of lead. For nickel and chromium, it is assumed that the rate of transfer is proportional to the lead transfer rate in the same ratio as seen in the wipe tests for the same type of string. These transfer rates are then multiplied by the 5,400 seconds (1.5 hours) assumed for the time spent playing each day.

For example, for the acoustic guitar string set Part No. Redacted (type N_Z), four of the strings, with diameters Redacted inches are wrapped with phosphor bronze wire covered with REDACTED. The scale length of an acoustic guitar is 26 inches (see above), so (1/4 x 26 + 2) inches worth of area of the strings is touched, giving a touched area of 23.95 cm^2. Multiplying by the wear rate of 0.0067 µg/cm^2/sec, the exposure time of 5,400 seconds, and a lead fraction of 0.05% gives a lead transfer from the wrapped strings in the set of 0.43µg. Chromium, lead, and nickel wipe-test data for the phosphor-bronze wire covered with REDACTED were, on average,

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

0.059, 0.193, and 0.665 µg respectively, when corrected by the average of the blanks (Table 2), giving ratios to lead for nickel and chromium of 3.44 and 0.30 respectively, so the transfer of nickel and chromium are estimated to be 0.13 µg and 1.49 µg respectively.

For the nickel-plated and stainless steel wrapped and coated strings, and the plain (nickel-plated) strings, the transfer rate to fingers is obtained using the wear rate we obtained from Erfani et al. (2015) in Section 5.1.1, that is 0.00183 per second of the amount transferred by the first touch. The first-touch transfer is calculated from the wipe data as described above. This wear rate, multiplied by the first-touch transfer amount and the 5,400 seconds of daily exposure gives the estimated daily transfer from touches after the first.

For example, the first-touch transfers for the plain strings in Part No. Redacted are calculated to be 0.0065, 0.036, and 1.52 µg for chromium, lead and nickel respectively; when multiplied by 0.00183 and 5,400 these gives daily transfer estimates of 0.064, 0.36, and 15 µg respectively.

Adding the results for the first touch and subsequent touches for Part No. Redacted gives totals daily transfers to fingers of 0.24, 0.95, and 18.5 µg of chromium, lead and nickel respectively.

The fractions of these totals transferred to the right and left hands is calculated from the total areas touched by the five fingers on each hand. The left hand touches an area equivalent to the total area of 1/4 of the scale length of the strings, which varies by instrument (see above), and the right hand touches an area equivalent to the total area of 2 inches of the strings. The fraction transferred to the right hand varies from 18.6% to 23.9% for the different instrument types. As described in the main text, on the right hand 1/2 of this fraction affects the thumb, with the rest distributed to the other fingers; on the left hand, 1/5 is assumed to affect each finger equally.

Green Toxicology LLC
Crouch@GreenToxiciology.com
Green@GreenToxicology.com

Appendix B: Element Materials Technology Laboratory Report on Job Redacted

(Omitted)

Note: See Table 2 for sample IDs; those in the Laboratory Report with suffix "-R-" correspond with samples irrelevant here.

Green Toxicology LLC

Crouch@GreenToxiciology.com
Green@GreenToxicology.com